Operational Experience on the Cold Neutron Source at the OPAL Reactor

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ABSTRACT

The Cold Neutron Source (CNS) at ANSTO's OPAL Reactor has operated with near perfect reliability since July 2013, supplying cold neutrons to neutron scattering instruments for more than 300 days a year. This recent highly productive and reliable operational period had come after a 16-month rectification program in 2012-2013 that resolved major compressor and turbine faults in the helium cryogenic system. It has been underpinned by a more focussed approach by a team of analysts, engineers and technicians, fully supported by senior management in the organisation. Drawn from the in-house knowledge base developed over the major-fault-affected years, the CNS team has been able to quickly identify the root cause of minor faults and process anomalies and carry out rectification in a timely fashion to ensure the CNS and reactor's availability. A comprehensive Reliability Centred Maintenance (RCM) strategy has been developed, based on Failure Mode, Effects and Criticality Analysis (FMECA) methodology as part of the asset management program of the entire reactor facility. In this paper, we will share our experience with some examples of operational events. A successful project of upgrading the helium cryogenic system's PLC in 2014 will also be discussed.

1. Introduction

The OPAL Reactor at Australia Nuclear Science and Technology Organisation (ANSTO) is a 20 MW multi-purpose research reactor that carries out a range of commercial and scientific activities as its mission [1, 2]. The OPAL Reactor targets 300 days of operation per year and has reached the target in 2015. Each reactor cycle is about 30 days on average. The Cold Neutron Source (CNS) at the OPAL Reactor employs 20 L of liquid deuterium as the cold moderator, which is cooled and maintained in single phase by a helium refrigerator in a vertical thermosiphon [3]. The CNS is required to have availability over 98% in each reactor cycle to supply cold neutrons to seven neutron scattering instruments [4, 5], all of which are open to international users and have been substantially over-subscribed.

The OPAL CNS was fully commissioned in 2006. Between 2006 and 2012, it operated with availability less than 80% due to some major faults in the helium refrigerator [6, 7]. Those major faults were fully rectified in 2013 [8]. Since then, the CNS operated with near 100% availability. The rectification efforts in 2012/2013 included not only modifications to the helium refrigeration plant, but also re-structuring of the CNS team. The CNS team currently consists of a specialist adviser, two system engineers, a technician and a trainer who also specialises in PLC code. This is a "virtual" team because those individuals come from different units of the Reactor Operation organisation and report to their respective line managers. The CNS team meets regularly and discusses all the CNS issues.

The functioning of such a team is fully supported by senior management. A direct line from the specialist adviser to the Division General Manager and the Reactor Manager ensures matters of critical importance are communicated promptly. Although the CNS operated with near perfect availability since 2013, it has not been without faults. This team structure has ensured the best consensus decision was made on those occasions. Furthermore, the CNS team is now best positioned to do some strategic thinking on the important issue of ensuring long term health and reliability of the CNS.

2. Reliability Centred Maintenance

The Reliability Centred Maintenance (RCM) methodology was first developed for the Aviation industry in the early 1960s, in order to increase the reliability and availability of the aircraft fleets of the US armed forces and later, the commercial airline operators. In the 1980s it became more universally recognised in other industries utilising complex systems as a methodology to ensure that performance to company targets were maximised through the structured analysis of components functions and their previous failure history. The methodology has, in recent times, been implemented by several major global manufacturers and operators as the industry has moved to more structured Reliability, Availability, Maintainability and Safety (RAMS) programs.

The OPAL Reactor organisation adopts the RCM methodology and provides a performance focus to the operation and maintenance aspects of the CNS. CNS maintenance strategy is derived from its ability to efficiently maintain the system, to maximise availability and reliability. OPAL has incorporated the RCM methodology into its Failure Modes Effects and Criticality Analysis (FMECA), in order to underpin this requirement for the CNS.

The RCM process acknowledges the basic premises that each component of the CNS exists to provide a function. While the user or operator may not notice the failure of a component, they will notice that the CNS no longer performs the function that it was intended to undertake. Consequently, RCM attempts to plan maintenance not around the failure of any one component, but around the loss of the functionality required by the CNS. In order to achieve this, seven key questions are asked of the CNS asset in order to determine the best maintenance strategy.

1. What are the functions and associated performance standards of the CNS operation in its present operating context?
2. In what ways can it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable pro-active task cannot found?

The answers to the first four questions were developed by FMECA, assessing what are considered to be the critical components from reliability-prediction’s perspective. Having identified all of the failure modes and consequences in the FMECA stage, the CNS team conducts cross-functional reviews of the suggested maintenance activities. As such, engineering, maintenance and operation are actively engaged in a joint workshop environment to answer the final three questions in the RCM process and complete the associated FMECA worksheets. This RCM / FMECA approach has proven successful in ensuring that all parties understand the constraints that apply to the design and maintenance of the CNS and its sub-systems.

In the final development stage of the RCM / FMECA process, failure modes are analysed to determine whether the failure is evident, will affect safety, will impact the conformance to environmental regulations, or is operational or non-operational. Maintenance tasks such as condition monitoring, scheduled service or scheduled replacement are specified, depending on the operational effect of the failure.

OPAL has undertaken an extensive RCM analysis on the CNS and used this information to continuously develop a more efficient and effective maintenance strategy. OPAL has ensured that Original Equipment Manufacturers (OEM) provide extensive maintenance information on their equipment.

There are six main failure patterns usually exhibited by components in complex system like CNS, known as bathtub, end of life, wear out, wear in, random failures and infantile failure. A critical aspect of the maintenance development process is an understanding that not all components fail in the same manner. As such the maintenance strategy for each component of the CNS has been assessed on the basis of its failure pattern. As well as the failure pattern, another critical element of determining the best maintenance strategy for a component is an understanding of the key indicators to failure. If an impending failure is identifiable, it is possible to monitor such indications and conduct preventative maintenance prior to failure. This approach has been extensively taken at OPAL.

3. Helium Refrigerator PLC Upgrade

The original PLC in the helium refrigerator was a Eurotherm PC3000. Process control and logic was programmed using the GRAFCET structure. Although the PC3000 was highly reliable as well as flexible during ten years of operation, Eurotherm ceased production of this controller and we could no longer find a reliable supplier for a spare. To ensure long term guarantee of supply, we decided to replace the PC3000 with a new PLC that was more widely used in the industry thus more easily accessible in the market. The package of work was contracted to an experienced local firm who specialised in supplying PLC hardware and software for industrial process control. The contractor offered Siemens S7 as the replacement PLC. The primary goal of the contract was to make a carbon-copy translation of the process program from PC3000 to S7. It was understood that although the contractor would be responsible for installing the new PLC and translating the software, the actual process tests would be conducted under the guidance and control of the ANSTO CNS team.

To minimise the plant's downtime, as much software-checking as possible was done prior to installation. The actual reactor shutdown time requested for commissioning was three weeks. The commissioning program consisted of multiple stages of verification of instrumentation I/O's (all field sensors), active control (e.g. all valves, heater controllers and a variable frequency drive), all normal process and maintenance subroutines and select fault subroutines. In the OPAL CNS, liquid deuterium is sub-cooled. The operation of the helium refrigerator is therefore by and large detached from the liquid deuterium condition. This allowed the refrigerator to be almost fully tested before it was necessary to raise the reactor to power for the full-heat-load test and the sudden-loss-of-heat-load test (i.e. reactor trip). The fault subroutines were selected to cover turbine protection functions and several known abnormal process conditions such as power outage to the compressors and power outage to the PLC itself. Some fault conditions were physically produced such as power outage. Others, such as low turbine bearing pressure or high turbine brake temperature, were produced by digitally forcing the sensor input to the PLC to avoid any mechanical risk to the turbine. However the protective action as a result of the fault signal was allowed to be executed in full by the new program for verification.

Another critical job during commissioning was to tune all the PID controllers in the program, including the compressor high/low (or discharge/suction) pressure controller, the turbine speed controller, the turbine bearing temperature controller, the turbine outlet pressure controller and the CNS helium inlet temperature controller. The controllers' configurations were initially copied from PC3000. Each of them was closely monitored during the tests and re-tuned when necessary (e.g. when excessive overshoots or oscillations took place). As a result, at the completion of commissioning, the new program was more than just a carbon copy of the old program in terms of functionality and equipment safety protection, but an improved version that could handle some transient conditions more smoothly.

The PLC upgrade project was completed on budget and on time. It signified the transfer of PLC ownership from the refrigerator OEM to ANSTO. The easy accessibility of a local firm has brought tangible benefits that should not be under-estimated. At the present time, there are continuing efforts by the CNS team in collaboration with the contractor to fix legacy bugs and make improvements in process control logic.

4. Helium Purity Control

It is conventional wisdom within the industry that gas purity control is paramount in a cryogenic plant such as an expansion-turbine-based helium refrigerator like ours. High levels of impurity can be a major cause of process faults such as heat exchanger degradation or even clogging and turbine failure. In the history of the OPAL CNS helium refrigerator, impurities such as nitrogen (from two different sources which are air and the purging gas), alcohol (from compressor oil degradation by oxidation or shear by the screws) and hydrogen (from compressor oil degradation) have been identified. We know with certainty that excessive amount of nitrogen can cause mechanical damage to the turbine wheel during warm-up when nitrogen “ice balls” can be blown off from the cold box adsorber. We also know with certainty that alcohol, so volatile that it cannot be trapped by the charcoal adsorber in the compressor oil removal skid, finds its way into the cold end of the turbine bearing and condenses there, causing shaft seizure. Hydrogen, due to its low condensation temperature, poses no direct risk to the refrigerator as a free gas, but it is a strong indicator of failures elsewhere in the process. The experience of failures, mostly due to OEM design faults which have all been identified and rectified, nevertheless has taught us a lot about the plant’s functionality and characteristics.

The purity of helium in the refrigerator used to be monitored by taking a sample and have it analysed in an external gas chromatograph instrument. In June 2015, there was an incident where 3000 ppm of nitrogen was measured to be in the helium due to inadequate purging after charcoal replacement in the oil removal skid. Our helium refrigerator does not have a secondary purifier such as a liquid-nitrogen pre-cooler. The only way to cool the helium is to run the turbine. One option was to completely replace the helium inventory by fresh gas bottles, which would be costly and time consuming. Under time constraint to start the refrigerator to allow the reactor to return to power on schedule, we decided to use the refrigerator to “clean itself” instead, that is, to run the turbine down to about 80 K knowing that nitrogen does not pose a direct risk to the turbine as long as the refrigerator is not permitted to warm up (to avoid the nitrogen ice ball scenario), stop the turbine shortly after 80 K is reached and perform a regeneration of the cold box charcoal adsorber to remove the nitrogen. The method took about 10 hours and worked. Nitrogen level dropped from 3000 ppm to 100 ppm, which was acceptable for *entering* normal operation. Note the actual nitrogen level during normal operation is below the detection level of 1 ppm. The reason for the residue 100 ppm after the *quick regeneration* was that not the entire buffer volume of the helium inventory had the time to circulate through the cold box.

Since the incident, a flame-spectroscopy-based multi-channel gas detector has been installed in the helium refrigerator which can give us in-situ reading of nitrogen and moisture levels in real time. We have used it to verify the self-cleaning method with a small amount of residue nitrogen in the system. The data consistently shows that nitrogen is in fact completely adsorbed in our cold box charcoal at 150 K, as shown in Figure 1, much higher than the 77 K condensation temperature. The self-cleaning method based on quick regeneration is a very effective way to purify the helium after maintenance should an abnormal high level of nitrogen be present. It poses no risk to the turbine.

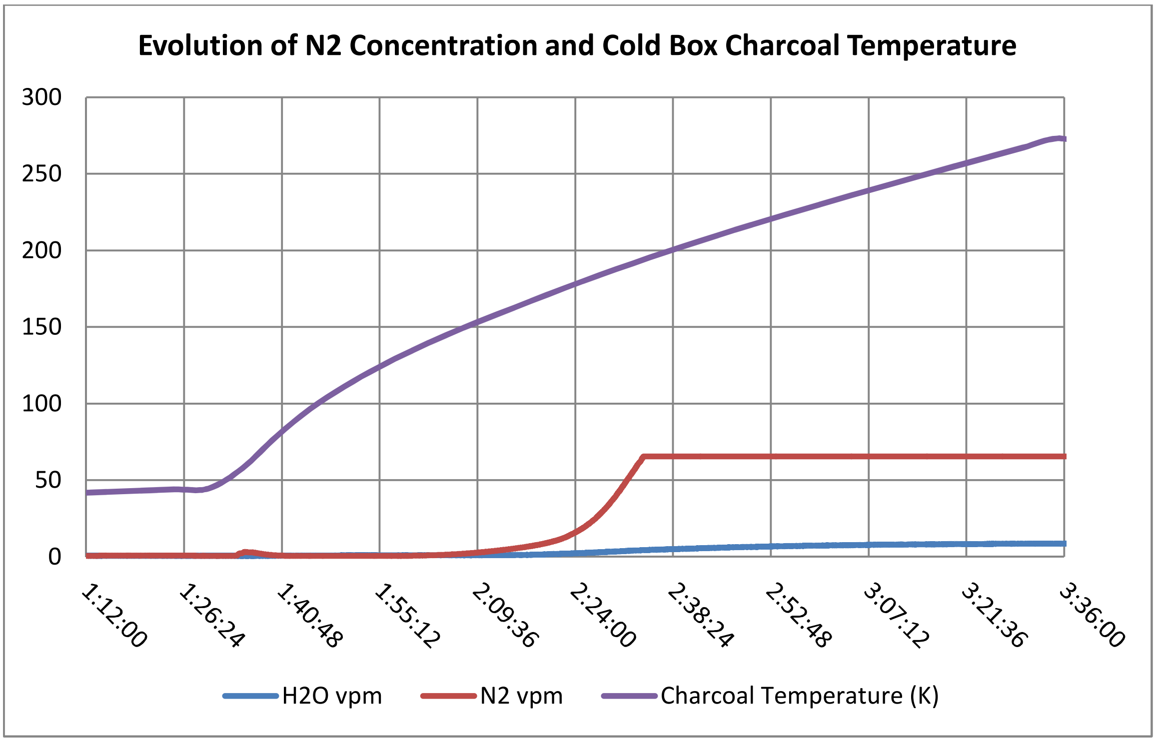

Figure 1 Nitrogen adsorption by charcoal to below 1 ppm level at temperature < 150 K. The instrument reading saturates at 60 ppm.

5. Helium Refrigerator Heater Controller Fault

In a study published in 2009 [9], accurate measurements of the OPAL CNS nuclear heat load as well as the non-nuclear heat load were reported. The nuclear heat load is around 3.6 kW at reactor full power of 20 MW. The same study also demonstrated that liquid deuterium was in sub-cooled state in the thermosiphon. The non-nuclear heat load was measured to be 388 W at the time, but we have observed an increase since then, most likely due to neutron activation of the structural material in the CNS over many years of full power reactor operation. By thermal balance during routine operation, the total CNS heat load is estimated to be about 4.5 kW at present. In April 2015, two years after the full rectification of the helium refrigerator, we ran a series of tests to determine its maxmum cryogenic power. By forcing the turbine to work at full speed, the helium temperature set point was incrementally lowered until both compressors were running at full speed. At that point, the refrigerator was “full”. The measured cryogenic power was 6.2 kW at 19 K, 37% (1.7 kW) more than the CNS requirement. The margin is quite substantial.

Because liquid deuterium is sub-cooled in the OPAL CNS, the helium inlet temperature to the CNS is fixed and does not depend on deuterium pressure. The helium inlet temperature’s set point is ensured by an in-line heater which has a fast response. Heat load change typically happens during liquefaction, evaporation or reactor power change. Normally the helium inlet temperature can be maintained well within 0.1 K of the set point of 20.5 K. In February 2014, it was observed that the helium inlet temperature was unusually noisy with an oscillation magnitude over 0.5 K. It was also observed that the CNS heat balance was off by more than 1 kW, although we were confident that deuterium remained in liquid state. It was first thought that the CNS thermosiphon might have reversed its flow direction which caused heat transfer instability. That possibility was ruled out after we raised the helium temperature to boil off some liquid deuterium and re-liquefied, only to see the temperature instability remained. It was also speculated that there might be a leak in the turbine by-pass valve (6290-PV-698 in Figure 2), letting through a warm flow of helium which brought extra heat load. Calculations revealed that for this scenario to happen the turbine by-pass valve would have to be wide open, which was extremely unlikely given that the very same valve seemed to be controlling certain transients as accurately and precisely as expected.

The root cause of the problem was finally determined to be a faulty heater controller. Measurements of its output voltage and current revealed that there was a discrepancy of 1 kW between the controller's indication and the actual power output to the heating elements. By replacing the heater controller, the fault was then completely cleared. Even though this fault was due to unpredictable electronic failure, it is important to note that the margin in the refrigerator cryogenic power was adequate to overcome the extra heat load from the faulty heater controller and keep the CNS functional, i.e. keep deuterium in liquid state, and save the neutron instrument scientists from disappointment for a whole reactor cycle.

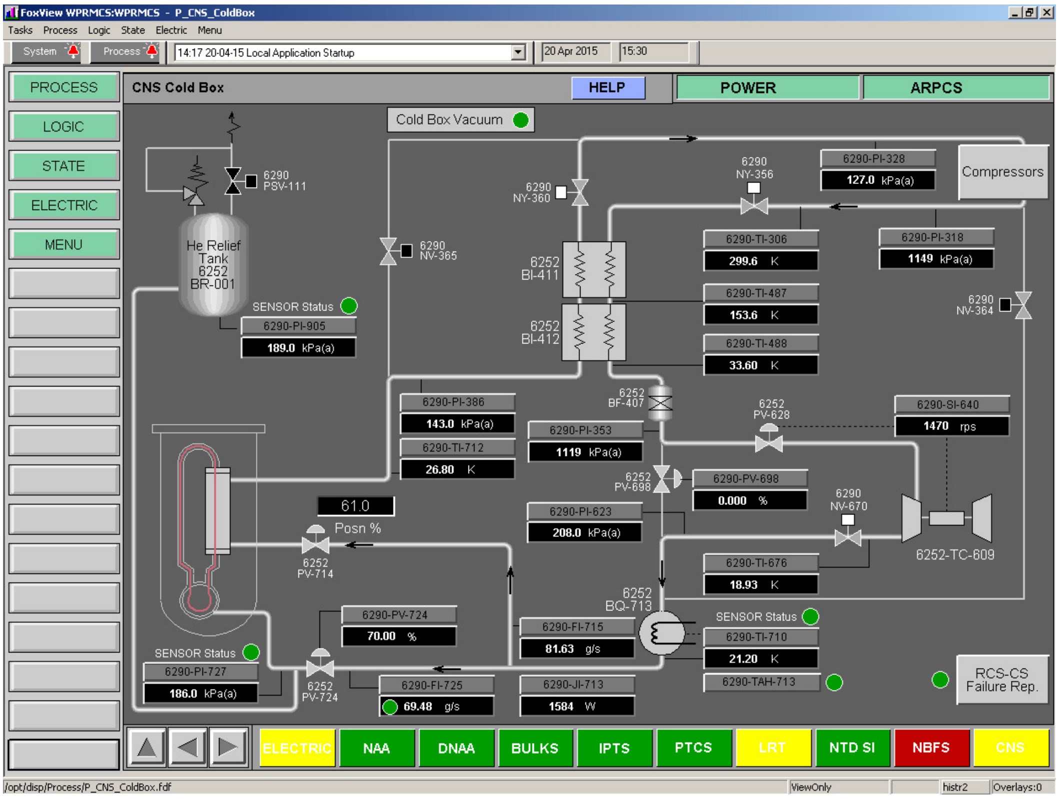

Figure 2 A simplied cold box P&ID showing the helium refrigerator operating at full capacity of 6.2 kW

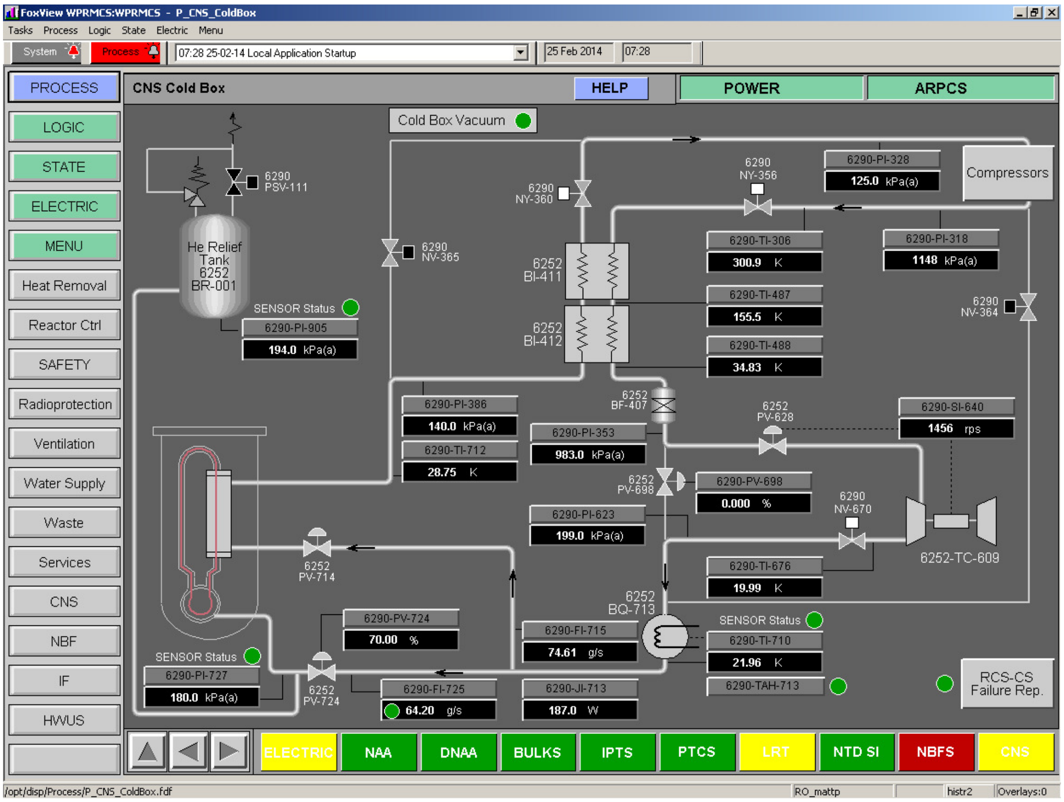

Figure 3 A simplified cold box P&ID showing the status of the helium refrigerator when the heater controller output (6290-JI-713) was off by over 1 kW

6. Summary

The OPAL CNS has operated reliably since its major rectification in 2013. In order to build up the knowledge base and ensure the best informed decisions are made during routine operation and maintenance, we have taken a team approach in the OPAL organisation. We described a RCM based maintenance strategy that has been adopted. Some of the operational events were discussed, including minor faults and their rectification.

7. References

[1] Miller, R. and Abbate, P.M., “Australia’s New High Performance Research Reactor,” IGORR 9 Conference Proceedings, Sydney, Australia, 2003.

[2] Hergenreder, D.F., Lecot, C.A., Lovotti, O.P., Villarino, E.A., Braoudakis G., Ersez, T., “Contract performance demonstration tests in the OPAL,” IAEA-CN-156, Proceedings of the International Conference on Research Reactor: Safe Management and Effective Utilization, Sydney, 2007, IAEA, Vienna (2008)

[3] Bonneton, M., Lovotti, O., Mityukhlyaev, V. and Thiering, R., “Installation and testing of the OPAL (ANSTO) Cold Neutron Source,” IGORR 10 Conference Proceedings, Gaithersburg, DC, USA, 2005.

[4] S. J. Kennedy, “Construction of the Neutron Beam Facility at Australia’s OPAL Research Reactor,” Physica B 385-386, 949-954 (2006)

[5] Close, F., Constantine P., Kennedy, S. J. and Robinson, R. A., “The Neutron Beam Expansion Program at the Bragg Institute”, Journal of Physics: Conference Series 528 (2014) 012026

[6] Lu, W. and Thiering, R., “Using a Multi-Parameter Monitoring Methodology to Predict Failures in the Cryogenic Plant of the Cold Neutron Source at Australia’s OPAL Reactor,” Advances in Cryogenic Engineering, AIP Conf. Proc. 1434, 1537-1542 (2012)

[7] Thiering, R., Taylor, D. and Lu, W., “Helium Refrigerator Maintenance and Reliability at the OPAL Cold Neutron Source,” Advances in Cryogenic Engineering, AIP Conf. Proc. 1434, 1543-1550 (2012)

[8] Lu, W., “Rectification of the OPAL Cold Neutron Source Cryogenic System,” IGORR 15 Conference Proceedings, Daejeon, South Korea, 2013

[9] Lu, W. and Thiering, R., “The OPAL Cold Neutron Source Heat Load Measurements,” IGORR 12 Conference Proceedings, Beijing, China, 2009